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DESIGN AND ANALYSIS OF A MASTER CYLINDER FOR HYDRAULIC BRAKING SYSTEM

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ABSTRACT

Brakes being the major safety system in a vehicle, plays an important role in automobile. It is responsible for bringing the moving vehicle to standstill as and when needed. Its effectiveness is of great concern for all brake engineers. Braking system working on hydraulic principle is called as Hydraulic braking system. The most significant part of a hydraulic braking system is a Master cylinder. This paper studies a conceptual design of a master cylinder, and its analysis primarily aiming on reducing its size without negotiating on its strength. Computer aided design model of a master cylinder was made in Creo parametric 3.0 and studied for stress and deformation under fatigue loading in ANSYS Workbench 15.0.

KEYWORDS: Master Cylinder, Hydraulic Braking System, Hydraulic Pressure, Leverage, CAD, Creo Parametric 3.0 & ANSYS Workbench 15.0

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Original Article

INTRODUCTION

Hydraulic braking system works on Pascal's law i. e. a change in pressure at any point in an enclosed fluid at rest is transmitted undiminished to all points in the fluid. In hydraulic braking system a master cylinder plays a vital role. It is the only pumping device which converts driver's force on pedal into required hydraulic pressure needed for stopping a moving vehicle. Thus, the force applied by driver at one point in the brake circuit acts equally on the wheels and leads to its braking. A general layout of a master cylinder is shown in Figure 1.

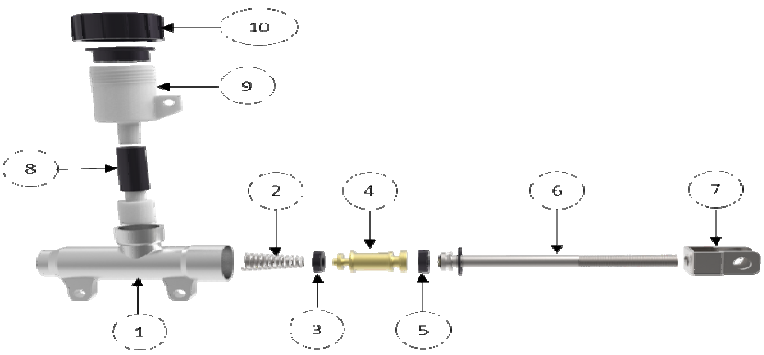

Figure 1: Exploded View of a Master Cylinder (CAD Model).

- Master cylinder body
- Conical compression spring

- Seal with peripheral slots
- Piston
- Packing seal
- Pushrod
- Fork
- Connector
- Reservoir
- Reservoir cap

WORKING

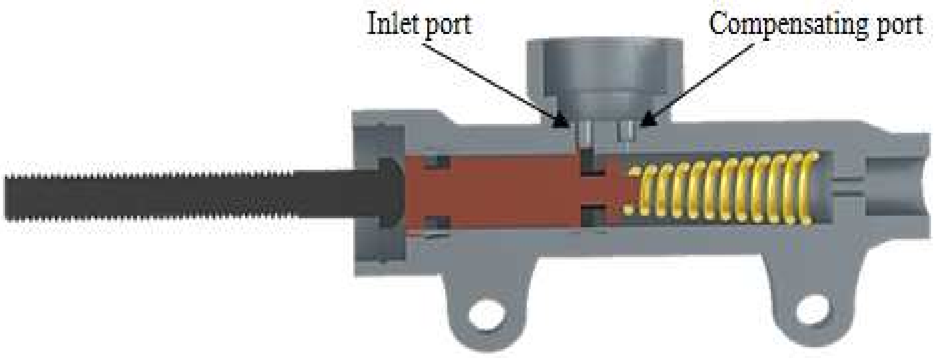

Figure 2: Normal Condition of Master Cylinder Assembly (CAD Model-Sectional View).

In normal condition when brakes are not applied the piston resides between the inlet and compensating port with spring being in released state as shown in Figure 2. This provides a fluid passage from reservoir to the cylinder.

When brakes are applied, the piston moves forward in the cylinder, thereby closing the compensating port and separating the pressurized chamber from the reservoir tank as shown in Figure 3. As piston moves further, hydraulic pressure starts building which is then transmitted to the wheels to lock them.

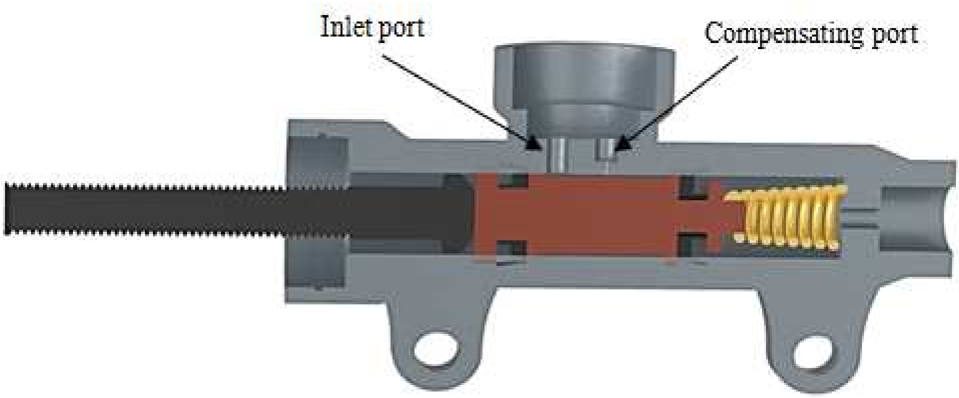

Figure 3: Brake Actuation Position of Master Cylinder Assembly (CAD Model-Sectional View).

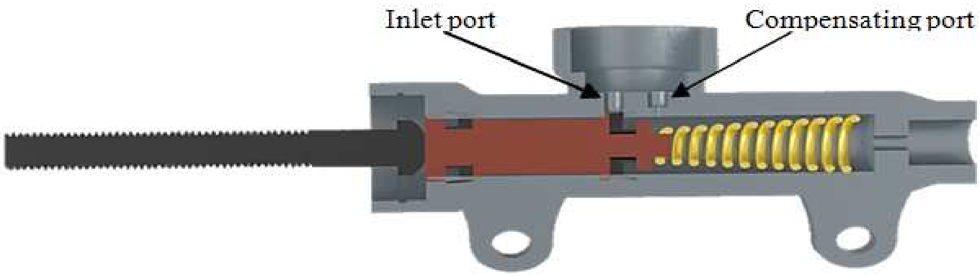

Figure 4: Brake Release Position of Master Cylinder Assembly (CAD Model-Sectional View).

When the brake is released the piston returns to its original position immediately due to the restoring force applied by the compressed spring. Since the fluid does not return to master cylinder immediately, the pressure in the cylinder drops. As a result, the brake fluid inside the reservoir tank flows into the cylinder via the inlet port, through small holes (orifices) provided at the front seal of the piston, and around the piston cup. This design prevents vacuum from developing and allowing air to enter at the caliper. After the piston has returned to its original position, fluid returns from the caliper circuit to the reservoir through the compensating port as shown in Figure 4.

CALCULATIONS

Master Cylinder Body

When the driver applies force on the pedal, the pressure is built up inside the master cylinder. This pressure depends upon the pedal force, pedal leverage and Master cylinder bore diameter. With a large pedal force, pedal leverage and small bore-diameter, a high pressure is built up inside the Master cylinder. The Master cylinder behaves like a pressure vessel with a pressurized fluid inside it. Thus, the wall thickness of Master cylinder body is calculated using equation (1) and (2):

$$\frac{\sigma x}{S.F} = \frac{b}{x^2} + a \tag{1}$$

$$Px = \frac{b}{x^2} - a \tag{2}$$

Where,

σx = hoop stress at distance x (MPa)

Px = pressure at distance x (MPa)

x = distance from center of cylinder (mm)

S. F = safety factor

a and b are constants, their value can be found out using boundary conditions.

Mounting Points

The mounting points of Master cylinder need to be sturdy enough to hold it upright. To ensure that, the mountings are to be subjected to shear failure using equation (3) and crushing failure using equation (4).

For shear failure,

$$(d2-d1)\ t\ \tau = P \tag{3}$$

For crushing failure,

$$d_1 t \ \sigma c = P \tag{4}$$

Where,

d1 = Inner diameter (mm)

d2 = Outer diameter (mm)

t = Thickness (mm)

P = Load (N)

τ= Shear stress (MPa)

σc = Crushing stress (MPa)

Spring Selection

The spring used in the master cylinder needs to be stiff enough to drive the piston back to its original position. Generally, conical compression springs with big-end resisting against the cylinder wall and small-end engaging the piston tip are used. Conical compression springs replaces cylindrical/axial springs where the axial space is limited.

The spring stiffness can be found out using the below equations (5) and (6):

$$\mathrm{Dm} = \frac{D_1 + D_2}{2} \tag{5}$$

$$R = \frac{Gd^4}{8ND_m^3} \tag{6}$$

Shear stress is calculated using equation (7),

$$S = \frac{8K_a D_m P}{\pi d^3} \tag{7}$$

Where,

Dm = Mean diameter (mm)

D1 = Diameter at small end (mm)

D2 = Diameter at big end (mm)

R = Spring stiffness

d = Wire diameter (mm)

G = Modulus of rigidity (GPa)

N = Number of active coils

Ka = Wahl’s factor

P = Axial Load (N)

S = Shear stress (MPa)

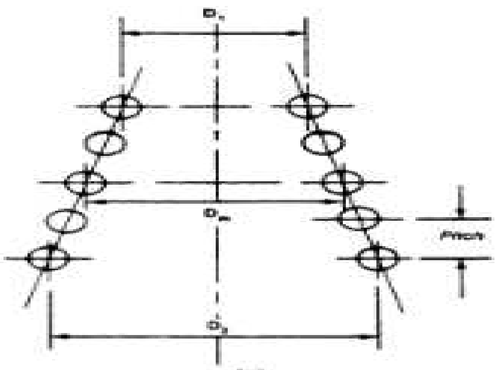

Figure 5: Schematic of Conical Spring.

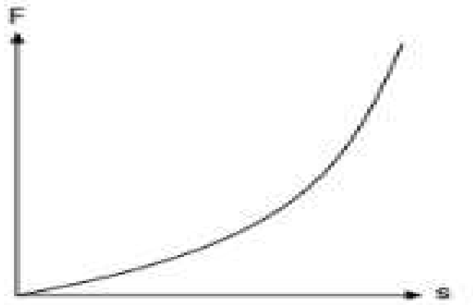

Figure 6: Load vs Deflection.

The characteristic behavior of a conical compression spring is shown in Figure 6**.**

MATERIALS

The material of master cylinder body must be stiff enough to partake less deflection. For a master cylinder, its stiffness is much important than its strength. Hence, the material must possess properties having high modulus of elasticity. Master cylinders of commercial vehicles are casted bodies having high modulus of elasticity (200–210GPa) and good machinability. Though being cheaper they weigh more due to higher density than other materials. Materials such as aluminum, plastic, polymeride, etc. can be used to get required strength and stiffness.

Piston can be made of alloys of aluminum. Since the only function of piston is to slide in the cylinder against the spring force. Hence, lighter materials such as plastic polymers can be used which has adequate strength to serve the purpose well.

Conical spring is used in special applications where spring rate increases with increase in load as desired. Also, buckling tendency of conical spring is less than normal helical spring. The springs are mostly made from oil-tempered carbon steel wires. Non-ferrous materials like phosphor bronze, beryllium copper, Monel metal etc., may be used to increase fatigue resistance, temperature resistance and corrosion resistance.

MOUNTING

The mounting of a master cylinder must be designed to be rigid enough to avoid any displacement of the master cylinder in the event of braking. Hence, the mounting must be designed considering the worst-case braking force applied by the driver onto the pedal. A high pressure is generated inside the master cylinder once brakes are applied. The mounting must be capable to withstand such high pressure for a number of cycles without failure. The mounting should be provided on the master cylinder as well as on the chassis without any manufacturing error. The material selection of the mounting plays a significant role in this process. Two mounting locations are suggested to make the mount steady and rigid. Extensions on the master cylinder should be provided while designing of master cylinder itself. The mount to be provided on chassis must have good welding properties. AISI 4130 (chromoly) metal sheet of certain thickness can be selected over AISI 1018 steel. This material has excellent weld ability, high strength to weight ratio and is easily available. The thickness of the mounting plate and the radial clearance to be provided from the mounting hole to the extreme fiber should be decided by the force analysis done in ANSYS Workbench module. This procedure essences to explain not only designing a rigid mounting but also maintaining a light weight.

FINITE ELEMENT ANALYSIS

After performing the calculations and deciding the parameters like inner diameter & wall thickness of Master cylinder body, piston size, thickness of mounting, spring stiffness, etc. a 3D model was created using CAD software Creo Parametric 3.0. This model was subjected to pedal force and analyzed using ANSYS Workbench 15.0.

Material Properties

- Material: Al 7075.
- Density: 2700 kg/m3.
- Young's Modulus: 72 GPa.
- Yield Tensile Strength: 503 MPa.
- Ultimate Tensile Strength: 590MPa.

Meshing

Tetrahedral elements having 4 nodes were used for meshing the Master cylinder body. Since tetrahedral elements capture higher degree curvatures more accurately and require less solving time, they are preferred over brick elements. Failed elements were analyzed and amended manually in order to exhibit the following criteria of element quality:

- Aspect Ratio (less than 5:1).
- Skewness (less than 60 degrees).
- Tet collapse (greater than 0.5).
- Jacobian (greater than 0.7).

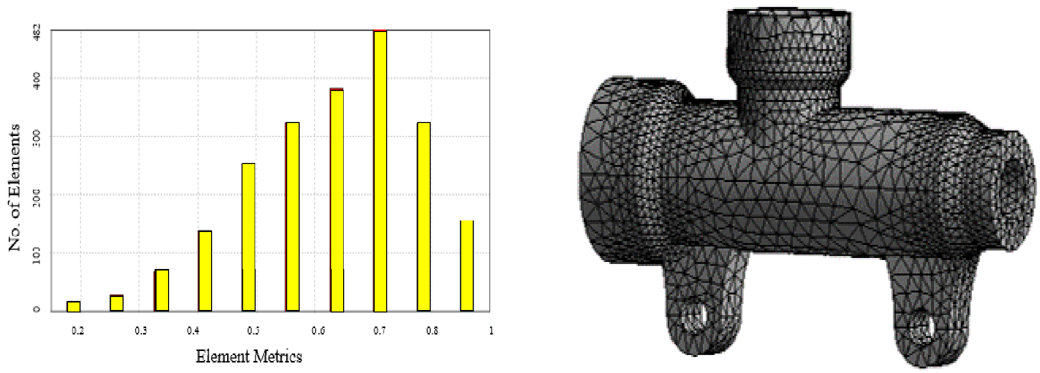

Figure 7: Default Mesh Quality Graph.

From the graph it is evident that the above mesh contains elements of various quality and the mesh is irregular. The mesh quality was improved by

- Geometry cleanup.
- Refinement at critical locations.
- Using advance proximity and curvature function.
- Using finer element size.

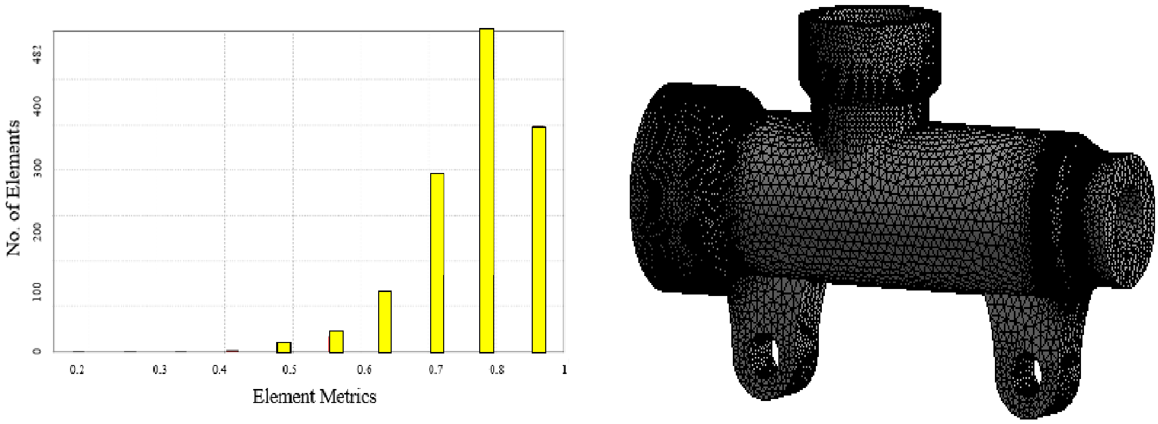

Figure 8: Improved Mesh Quality Graph.

The graph shown in Figure 8 indicates that the number of elements having higher quality are increased. Hence, more accurate results are generated.

Boundary Conditions

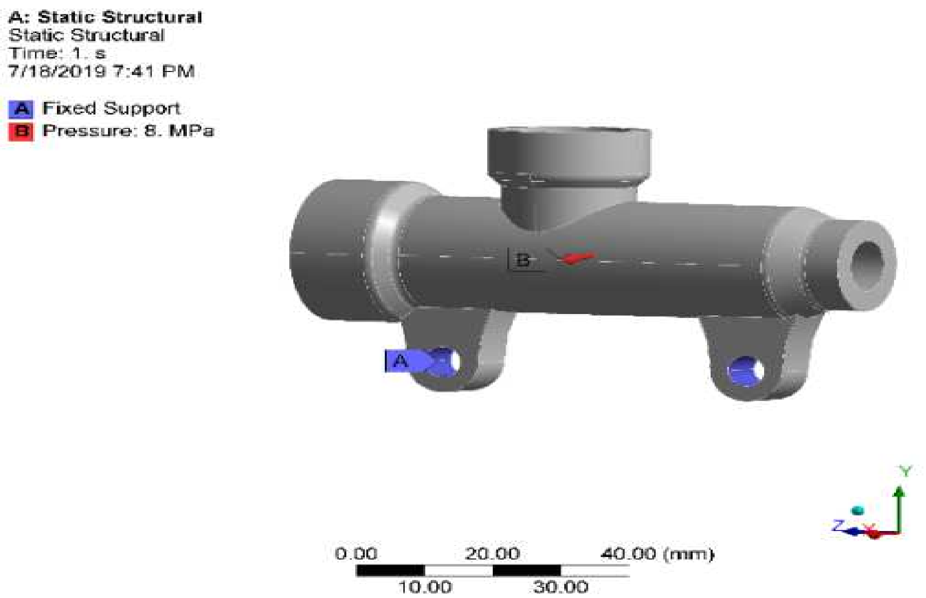

Figure 9: Boundary Conditions Applied in ANSYS.

The pedal force exhibited by the driver is considered. This force is multiplied by leverage of the pedal to give rise to pressure exerted over the inner bore of the cylinder. For a pedal force (F) of 200N, leverage (L) = 2*Diameter of master cylinder = 127mm, Pressure = F*L/Area = 8MPa. This pressure is applied to the cylinder's inner surface along the direction of movement of pushrod/piston. The fixed supports are applied at the mounting holes of Master cylinder body, as the Master cylinder is fastened to the chassis at these mounting locations. The direction of pressure applied, and the fixed support are shown in Figure 9.

RESULTS

The results obtained from ANSYS Workbench are shown in the following figures:

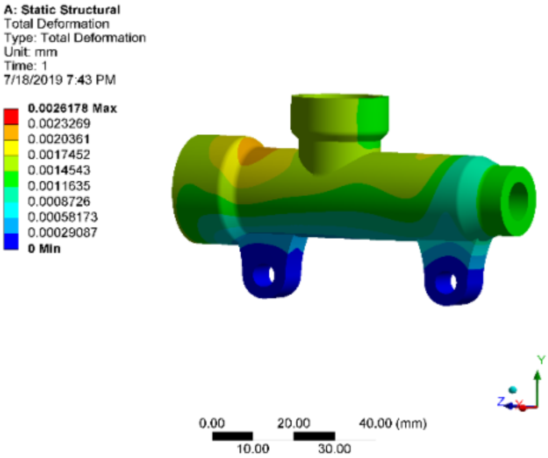

Figure 10: Stress Distribution.

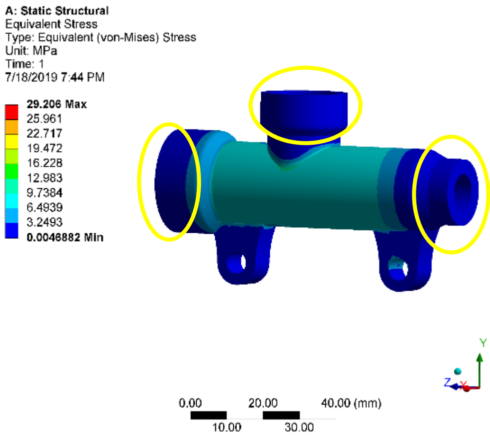

Figure 11: Deformation.

The results show that for an applied pressure of 8MPa, the maximum stress induced on the master cylinder body is close to 30MPa. The maximum deformation of the casing is less than 1mm. The safety factor value comes around 7.6. The areas shown in Blue (marked by yellow rings) in Figure 10 are the ones where weight reduction can be done to further achieve an optimized design.

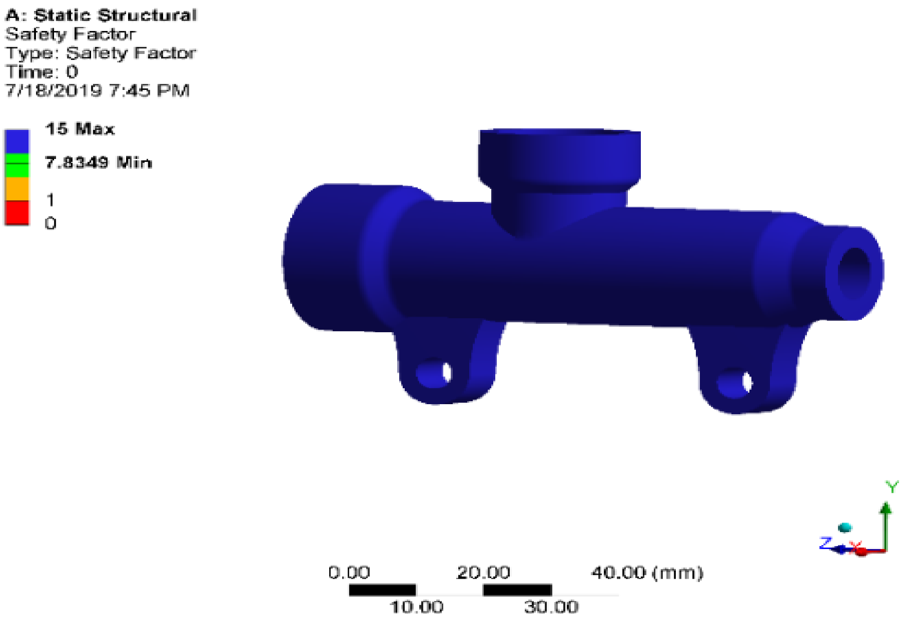

Figure 12: Safety Factor.

CONCLUSIONS

This paper studies, in detail, conceptual design, working, and analysis of a Master cylinder. An attempt was made to design a light-weight Master cylinder considering various parameters and was analyzed for stress distribution, deformation and safety factor using Finite Element Analysis. Major focus was boarded on design of low weight master cylinder casing, its mounting and spring selection. It also focusses on the methods of improving mesh quality. The results obtained from analysis helps to predict the safety factor of the component and throws light on regions where further weight reduction can be done to achieve an optimized design. After carrying out static structural analysis, further optimization of master cylinder body can be done by using Shape Optimization tool of ANSYS and target oriented weight reduction can be achieved.

Depending upon the usage and number of cycles of application, safety factor can be decided, and an optimized design of Master cylinder weighing less than 250 grams can be achieved by following the procedure elucidated in this paper.

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